EXTRAGALACTIC THICK DISKS

Implications for Early Galaxy Evolution

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Abstract I briefly review the growing evidence that thick stellar disks surround most edge-on disk galaxies. Recent studies show that these extragalactic thick disks have old ages, low metallicities, long scale lengths, and moderately flattened axial ratios, much like the thick disk of the Milky Way. However, the properties of thick disks change systematically with the mass of the galaxy. The thick disks of low mass galaxies are more prominent and somewhat more metal-poor than those surrounding massive disk galaxies. Given the strong evidence that thick disks are fossils from an early epoch of merging, these trends place tight constraints on the early assembly of disk galaxies.

Introduction

Although thick disks are best known as a component of the Milky Way, they were actually first identified as extended faint envelopes surrounding other galaxies (Burstein (1979); Tsikoudi (1979)). The subsequent discovery of a comparable stellar component in the Milky Way (Gilmore & Reid (1983)) drew attention away from the ambiguous interpretation of faint features in external galaxies, and instead refocused it on the wealth of data available from photometric and spectroscopic observations of individual stars within the Galaxy. These studies quickly showed that the Milky Way's thick disk is a fossil relic from an early epoch in the Galaxy's formation (see reviews by Freeman & Bland-Hawthorn (2002); Norris (1999); Majewski (1993); Gilmore et al. (1989)). Its stars are old and metal-poor ($\langle$[Fe/H]$\rangle$ $\sim$-0.7), and show an enrichment pattern that is distinct from thin disk stars with similar iron abundances (see the recent review by Feltzing et al. (2004)). These data suggest that the Milky Way thick disk is not a simple extension of the thin disk, but instead captures a unique episode early in the formation of the Galaxy.

Given the evidence above, how does the thick disk fit into the existing paradigm of disk galaxy formation? The ages of stars in the thick disk suggest

that they were formed more than 8 Gyr ago (Liu & Chaboyer (2000)), when the merging rate was likely to be high. It is therefore reasonable to assume that the formation of the thick disk is somehow coupled to the mergers and interactions expected to dominated in hierarchical structure formation. Within this scenario, thick disk stars could have acquired their current large scale heights and vertical velocity dispersions in three ways. In the first and widely held view, the thick disks stars were initially formed within a thin gas disk, but were then vertically heated by one or more interactions with a satellite galaxy (e.g. Quinn et al. (1993)). In the second, the thick disk stars were formed *in situ* at large scale heights during a burst of star formation, as clumps of gas coalesced to form the thin disk (e.g. Kroupa (2002); Brook et al. (2004)). In the third, the thick disk stars formed outside of the galaxy in the pre-galactic fragments, which then deposited the stars in the disk (Statler (1988); Abadi et al. (2003)).

Unfortunately, it is difficult to discriminate among these very different scenarios using data from the Milky Way alone. It is therefore time to return to the broader range of galaxies that can be probed with studies of extragalactic thick disks. In the intervening years between the initial detections of Burstein (1979) and Tsikoudi (1979), there has been a steadily growing body of detections of thick disks in other galaxies (e.g. Neeser et al. (2002); Wu et al. (2002); Matthews (2000); Abe et al. (1999); Fry et al. (1999); Morrison et al. (1997); Naeslund & Joersaeter (1997); de Grijs & van der Kruit (1996); van Dokkum et al. (1994); Bahcall & Kylafis (1985); Jensen & Thuan (1982); van der Kruit & Searle(1981); see also the compilation in Table 2 of Yoachim & Dalcanton (2005b) and the review by Morrison (1999)). Recently, the pace of discovery has accelerated with the large early-type sample studied by Pohlen et al. (2004) and the late-type sample studied by Dalcanton & Bernstein (2002). In this review I first summarize the structures, stellar populations, and kinematics of the thick disk population, and argue that extragalactic thick disks are indeed reasonable analogs of the well-studied thick disk in the Milky Way. I then discuss how the growing body of data places strong constraints on the origins of thick disks, and on disk galaxy formation in general.

1. The Properties of Extragalactic Thick Disks

Until recently, most evidence for thick disks in other galaxies came from deep broad-band imaging. Starting with the seminal work of Burstein (1979) and continuing through the systematic work of Heather Morrison's group and others (see review in Morrison (1999)), analyses of vertical surface brightness profiles (i.e. parallel to the minor axis) of edge-on galaxies have typically shown breaks at large scale heights, indicative of a second, thicker disk component that dominates at large heights and faint surface brightnesses. More

recent studies have taken advantage of advances in computing power to fit the full two-dimensional light distribution to models of two superimposed disk components (e.g. Yoachim & Dalcanton (2005b); Pohlen et al. (2004)). In Figure 1 I show the residuals from one- and two-disk fits to a large sample of edge-on late-type disk galaxies from the Dalcanton & Bernstein (2000) sample, as analyzed in Yoachim & Dalcanton (2005b). Fits to only a single disk leave large amounts of light at high latitudes, providing convincing evidence that there is an additional, thicker stellar component. Fits that include a second disk component do a far better job of fitting the light distribution, at all latitudes.

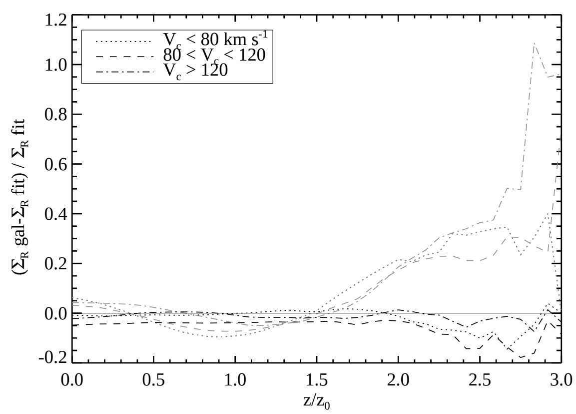

Figure 1. Residuals from single-disk (light lines) and two-disk fits (dark lines) to edge-on galaxies in different mass ranges (Yoachim & Dalcanton (2005b)). All of the single-disk fits show large positive residuals at large scale-heights, for galaxies in every mass range. In contrast, including a second thick disk component reduces the residuals to $< 10\%$ at all scale heights.

The Structure of Thick Disks

Generically, all of the disk galaxies studied to date have some degree of excess light at high latitudes. While the extra-planar light seems to be well fit by an additional thick disk component, there is no guarantee that this second component is strictly analogous to the well-studied thick disk of the Milky Way. Within the Galaxy, one can identify thick disk stars by their distinct kinematic and chemical properties, whereas two-dimensional decompositions of galaxies typically have non-unique solutions that depend on the weighting, the bandpass, and the assumed underlying model.

In spite of these uncertainties, there is growing evidence that the population of extragalactic thick disks revealed by two-dimensional disk fitting are reasonable (though probably not exact) analogs of the Milky Way's thick disk. Struc-

turally, the secondary disk components are quite similar, and are well matched to the scale heights, scale lengths, and axial ratios ($\sim$3-4:1) of the Milky Way thick disk, when restricted to galaxies of comparable mass (Yoachim & Dalcanton (2005b)).

While it is not too surprising that extragalactic thick disks are indeed thick, other unexpected structural results have been revealed by the rapid increase in the number of well-studied systems. In particular, the thick disk component is almost always more radially extended than the embedded thin disk. Figure 2 shows the scale length ratio of the thick to thin disks from a wide variety of studies in the literature. In almost all cases, the thick disk has a longer scale length.

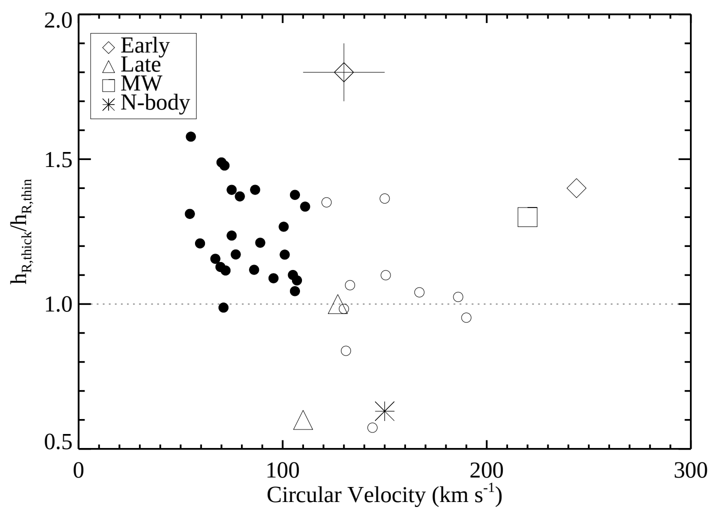

Figure 2. The ratio of thick disk to thin disk exponential scale length, as a function of galaxy rotation speed for the late-type galaxies from the Dalcanton & Bernstein (2000) sample (closed and open circles) and other individual studies (triangles; Wu et al. (2002); Neeser et al. (2002); Abe et al. (1999)), the Milky Way (square; Larsen & Humphreys (2003)), the Pohlen et al. (2004) sample of S0's, and numerical simulations of Brook et al. (2004). In almost all cases, the thick disks have longer scale lengths than their embedded thin disks.

The Stellar Populations of Thick Disks

In addition to their structural similarities, HST imaging is now revealing similarities between the stellar populations of the Milky Way and the extragalactic thick disks. Studies of resolved extraplanar stars (Seth et al. (2005a); Seth et al. (2005b); Mould (2005)) are finding that the stellar populations are systematically older at large scale heights. Figure 3 shows that stars above the

plane are dominated by old ($\sim 5-13\,\mathrm{Gyr}$) red giant branch stars, as discussed in more detail in Seth et al. (2005b). The colors of these extraplanar red giants indicate that they are exclusively metal poor, with a median metallicity of [Fe/H]$\sim$-1 in the low mass ($V_c \sim 75\,\mathrm{km\,s^{-1}}$) galaxies studied. The old red giant population seems to be well mixed vertically, and shows no evidence for the strong vertical metallicity gradients that would be expected if steady vertical heating had been solely responsible for driving each new generation of stars to larger scale heights (Seth et al. (2005b); Mould (2005)). A single vertical heating event, however, could be compatible with the lack of metallicity gradient, since the resulting thickened disk would be well-mixed.

Unfortunately, extraplanar stellar populations have been studied in fewer than ten galaxies to date, and usually in a single field. The number of future studies will be limited by the relatively small numbers of galaxies that are both edge-on and close enough to resolve into stars.

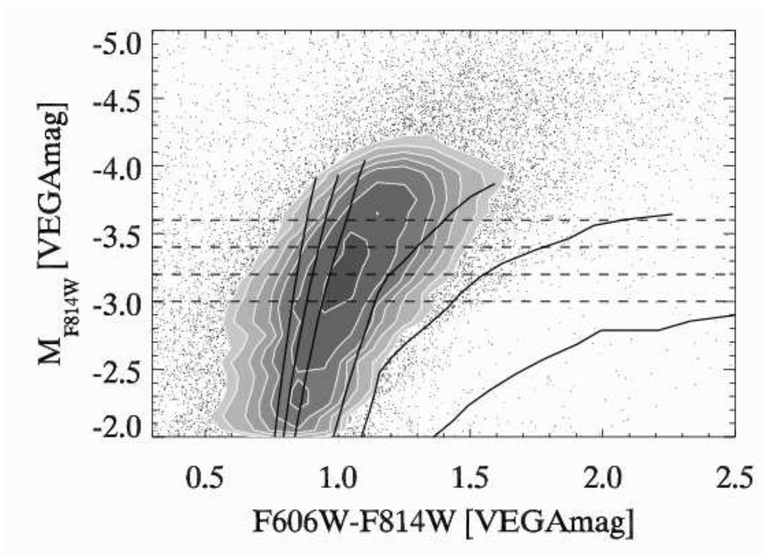

Figure 3. The color-magnitude diagram of stars more than 4 disk scale heights above the midplane, for all six galaxies in the Seth et al. (2005b) sample. The stars are clearly dominated by old red-giant stars, with no significant main sequence or AGB population. Solid lines show 10 Gyr old Padova isochrones for the RGB with [Fe/H] (from left to right) of -2.3, -1.7, -1.3, -0.7, -0.4, and 0.0. The peak of the stellar distributions fall between [Fe/H] of -1.3 and -0.7. For reference, the peak metallicities of the Milky Way's thick disk and stellar halo are [Fe/H]$\sim$-0.7 and [Fe/H]$\sim$-2.2, respectively.

The Kinematics of Thick Disks

The number of kinematic studies of extragalactic thick disks is even more sparse than the stellar population studies. Outside the Milky Way, there have only been two other published measurements of thick disk kinematics (Yoachim & Dalcanton (2005a)). All three cases reveal thick disks that rotate more slowly than the embedded thin disk. However, even within such a small sample, the thick disk kinematics seem to be relatively complex. Within the Milky Way, there is evidence at large scale heights of significant kinematically distinct populations that rotate even more slowly than typical thick disk stars closer to the midplane (Gilmore et al. (2002)). Among the two extragalactic thick disks studied, one shows clear evidence of *counter*-rotation. While larger samples are clearly needed before one can probe systematic variations, the current data already point to a significant degree of scatter in the relative kinematics of thick and thick disks.

2. How Do Thick Disks Form?

The data summarized above points to the following generic facts about thick disks that must be fit into the basic paradigm of disk galaxy formation:

- Thick disks are found in essentially all edge-on disks, at all Hubble types. They are therefore a generic by-product of disk galaxy formation.
- Although they are ubiquitous, there is substantial scatter in the structural properties of thick disks (see, for example, the scatter in Figure 2).
- The thick disk typically has a longer exponential scale length than the embedded thin disk.
- The stars in thick disks are dominated by old ($>5\,\mathrm{Gyr}$), relatively metal-poor (-1.5<[Fe/H]<-0.7) red giants, and are somewhat more metal-poor in lower-mass galaxies.
- The kinematics of thick disk stars vary widely, and show both co- and counter-rotation. However, in all cases the thick disk rotates more slowly than the thick disk.

Current models of disk formation assume that the bulk of a galaxy disk forms from accreted gas with high angular momentum. Analytic calculations assume that this gas is accreted steadily through spherical infall (e.g. Fall & Efstathiou (1980); Dalcanton et al. (1997); van den Bosch (1998)), but recent numerical simulations have shown that even the gas accreted through clumpy hierarchical merging can maintain sufficient angular momentum to produce realistic massive disks (e.g. Governato et al. (2004)). The accreted gas dissipates

and collapses into a rapidly rotating disk that then converts into stars, forming a thin disk.

Within this scenario, the natural sites of thick disk star formation are: [1] in the thin gas disk, which is later disrupted and vertically heated by satellite accretion; [2] in the merging gas clumps, as they coalesce into the thin disk (Brook et al. (2004)); or [3] in the pre-galactic fragments, before the disk is formed (e.g. Abadi et al. (2003); Yoachim & Dalcanton (2005b)). All three of these possibilities would naturally lead to the formation of the thick disk in a merging hierarchy. Moreover, because all three are tied to high merging rates (which peak early and decline sharply after a redshift of $\sim 1-2$), each of these scenarios naturally produces an early epoch of rapid thick disk formation, making them compatible with the old ages and high α-element abundances currently seen in thick disk stars.

Of these three scenarios, I believe that the third possibility – direct accretion of stars – is likely to dominate the production of the thick disk, although there is certainly room for the other two mechanisms to occur as well (and indeed, it would be surprising if they didn't to some degree). Although it is far more limited than the structural information currently in hand, the kinematic data strongly disfavors the vertical heating scenario. Vertical heating does little to change the angular momentum of a disk (Velazquez & White (1999)), thus making it difficult to explain why the thick disk rotates significantly more slowly than the thin disk, having no more than $\sim$50% of the rotational speed of the thin disk in all three cases studied. Likewise, it would be difficult to produce the very different scale lengths of the two disk components without their having very different angular momenta.

Long thick disk scale lengths are likewise difficult to produce in the second model, where thick disk stars form *in situ* as gas merges to form the final disk. In this case, the same accreted gas would form both the thin disk and the thick disk stars, making it likely that both would have similar radial distributions. Producing a thin disk with a shorter scale length would require that the gas left over after the thick disk stars formed had systematically lower angular momentum. This requirement seems a bit unlikely and is in conflict with the limited available kinematic data.

In contrast, the slower rotation speeds and longer scale lengths of thick disk stars drop out naturally if the stars were formed in pre-galactic fragments before being accreted onto the disk. Gas and stars behave differently during accretion, leading to a natural segregation in the properties of the thin and thick disk. The accreted gas (which forms the thin disk) can cool and dissipate, and thus will tend to contract further into the halo than the stars. As it contracts, the gas will speed up due to angular momentum conservation, producing a compact disk that rotates more rapidly than the accreted stars. In contrast, the orbits of the accreted stars cannot lose energy (except through dynamical friction),

and will tend to remain in a thicker, more radially extended distribution than the gas disk. This scenario thus naturally reproduces the larger scale height and scale length of the thick disk. Moreover, because not all of the merging satellites have the same gas-richness, some satellites may contribute the bulk of the stars to the thick disk while others contribute the bulk of the gas to the thin disk. Some kinematic and structural decoupling between the two components would therefore be expected, because different precursors may dominate production of the thick and the thin disks, and could thus easily produce the scatter seen in the observations.

If the majority of thick disk stars were indeed directly accreted, then the thick disk can constrain the typical gas-richness of the pre-galactic fragments from which the galaxy assembled. In this picture, any stars in the merging sub-units were deposited in the thick disk, while any gas cooled and settled into the thin disk. The relative baryonic mass fractions of the thin and thick disks therefore constrain the ratio of stars to gas in the early galaxy. In Yoachim & Dalcanton (2005b) we have inferred the luminosities of the thick and thin disks from the two-dimensional decompositions, and then adopted color-dependent stellar mass-to-light ratios to derive the stellar mass of each disk component. The resulting "baryon budget" is reproduced in Figure 4, as a function of galaxy mass for the late-type Dalcanton & Bernstein (2000) sample, after assuming that any gas is confined to the thin disk.

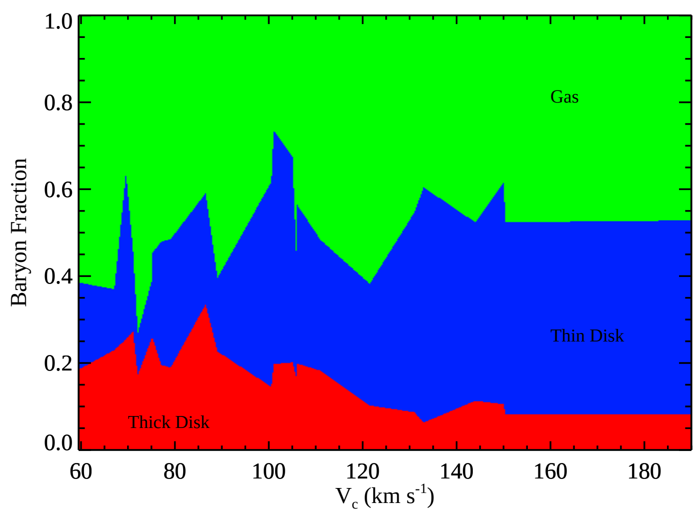

Figure 4. The baryonic mass fraction of the the thick disk stars (bottom), thin disk stars (middle), and cool gas (top) for the galaxies analyzed by Yoachim & Dalcanton (2005b), sorted by galaxy rotation speed.

Figure 4 shows a number of striking features. First, the baryonic mass fraction trapped in the thick disk is relatively small, implying that the initial galaxy disk was almost entirely gaseous ($\sim$75-90%, or more if some thick disk stars formed during the final coalescence of the disk). Second, the stellar mass of the thick disk is *larger* than the stellar mass of the thin disk in low mass galaxies. Thus, although low mass galaxies appear to be blue and young, the majority of their stars are actually quite old, as would be expected in hierarchical merging scenarios. Finally, the thick disk is increasingly important in low mass galaxies. The baryonic mass fraction locked in the thick disk increases systematically from $\sim 10\%$ in high mass galaxies to up to $\sim 25\%$ in low mass galaxies, implying that the precursors of low mass galaxies were more gas poor than the precursors of their high mass counterparts.

If thick disk stars are directly accreted, then the increasing importance of thick disk stars in low mass galaxies can be easily explained by supernova-driven winds in the pre-galactic fragments. The precursors of low mass galaxies are themselves likely to be lower mass than the typical sub-units which merge together to form more massive galaxies, and thus, they are more susceptible to gas loss through supernova driven winds. These winds would reduce the gas mass of the initial galaxy, and thus reduce the fraction of baryons that wind up in the thin disk. The winds would also reduce the typical metallicity of thick disk stars, and could thus nicely produce the trend toward lower thick disk metallicities in low mass galaxies (Seth et al. (2005b)).

3. Prospects for the Future

Decades of painstaking work have gone into observing and characterizing the population of extragalactic thick disks. Thanks to this effort, we now have a broad understanding of the basic properties of thick disks, allowing us to finally place them within the context of galaxy formation. However, while the broad outlines of thick disk formation are in place, there are many details to be worked out. Over the next decade, I believe there are several areas where thick disk research will be critical:

- **Exploring the link between observations of thick disks at low redshift and of young galaxies at high redshift ($z > 1.5$).** There are already hints that many of the stars in clumpy, disturbed galaxies at high redshift will evolve into the thick disk population by the present day (Elmegreen & Elmegreen (2005)). This likely connection makes ongoing work on low-redshift thick disks crucial for understanding and interpreting high-redshift observations.

- **Linking thick disk observations to numerical studies of galaxy formation.** Simulations are just now beginning to have the resolution to tackle thick disk formation (see work by Chris Brook and Alyson Brooks

in this volume). However, because the properties of thick disks depend on star formation and gas loss in dense low mass pre-galactic fragments, simulations of thick disk formation will be highly sensitive to the adopted star formation and feedback recipes, as well as to the numerical resolution. Thus, I believe we are only in the early days of numerical exploration of thick disk formation. Perhaps the greatest long-term role for extragalactic thick disks will be as a key calibration for tuning the baryonic physics in these simulations.

- **Incorporating the thick disk component into semi-analytic models of galaxy formation.** Given that the thick disk dominates the stellar mass in low-mass disks, a recipe for including thick disks in semi-analytic models is sorely needed.

- **Exploring the connection between thick disks and bulges.** To date, large studies of thick disks have focused on either bulgeless (Dalcanton & Bernstein (2002); Yoachim & Dalcanton (2005b)) or bulge-dominated (Pohlen et al. (2004)) galaxies. However, there is currently no study using uniform data and analysis techniques to bridge across this wide range of galaxy types. There are hints that thick disks may be systematically "thicker" in early type galaxies (Yoachim & Dalcanton (2005b)), but without uniform data, the robustness and interpretation of such conclusions is questionable. Theoretically, there is much work to be done as well. Mergers are thought to be critical to the formation of both thick disks and massive bulges, but we currently have no well-developed theory that can reliably calculate how the merging material is distributed between the bulge and the thick and thin disks.

- **Observationally and theoretically untangling thick disks and stellar halos.** As difficult as it has been to characterize extragalactic thick disks, the upcoming work to isolate stellar halos will be even harder. In the Milky Way, the thick disk makes up roughly 10% of the stars at the solar circle, while the stellar halo contributes only a tenth of a percent (Chen et al. (2001)). Even with detailed studies of resolved stars (e.g. Ferguson et al. (2002)), it is difficult to decide whether a given structure is an analog of the Milky Way's thick disk or its halo, if indeed they are truly distinct structures. Already, there have been extraplanar stars attributed to the thick disk that are probably distributed in a much more spherical distribution (e.g. Tikhonov et al. (2005)) and which may be better assigned to an analog of the stellar halo. Simultaneously, theoretical models of stellar halo formation (Bullock & Johnston (2005)) produce distributions of stars that can be relatively flattened in their inner, higher surface brightness regions. Given the only modest flattening ($\sim$3:1) of

extragalactic thick disks, it is possible that these are the same structures, in spite of the different nomenclature. As more simulations are translated to the observational plane, the correct interpretation of broad-band colors and resolved stellar populations in edge-on disks will clarify.

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